Transformer failures within Southern Africa

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The unexpected failure of a power transformer can result in a very large forced outage cost and there is a need to detect and locate suspect units rather than wait for failure.

When faults do occur, there is a need to identify the type and location of the fault rapidly, thus reducing downtime. This places great importance on diagnostic testing and the interpretation of results.

Oil testing methods

Dissolved gas analysis (DGA), furans and oil quality tests are very well established and have proved to be a valuable tool in transformer fault diagnosis.

Dissolved gas analysis

There are a number of different DGA techniques such as IEC, Roger's Ratios, IEEE, etc. that have been used with great success. These methods suffer from drawbacks like their inability to determine a normal operating transformer and returning of codes with no diagnosis. However, DGA does give warning of a developing fault that can prompt further investigation.

Oil quality indicators

Oil quality indicators such as moisture (from which relative saturation is calculated), acidity, dielectric strength and interfacial tension are excellent indicators of ageing oil. Poor results normally result in purification and/or regeneration of the transformer oil and it some cases oil replacement.

Paper condition indicator

The concentrations of paper degradation product 2-furfural (2FAL) provide an indication of the condition of the paper. However, there are a number of factors that influence the concentration and stability of furanic compounds such as temperature, type of paper used, oil treatment, etc. The conventional method is to convert the 2FAL value to a degree of polymerization (DP) by applying the Chendong equation which can be used to provide a general sense of the average DP based on the 2-furfural content. However, it is always best to have some DP data for a given population to verify the relationship. The rate of increase in furans between samples is also a strong indicator of paper ageing.

Electrical tests

The following electrical tests are used to determine the condition of the transformer:

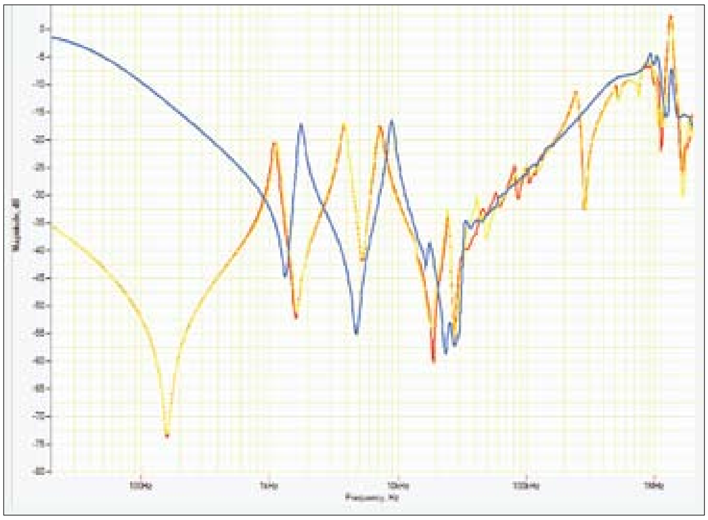

Fig. 1: HV to MV winding response.

Fig. 2: Blue phase tapping leads and broken cleats.

Fig. 3: Flash marks on fixed contacts and collector rings.

Condition	Test
Dielectric	DGA, furans, winding insulation, ratio, insulation resistance
Thermal	DGA, exciting currents, DC winding resistance and IR scanning
Mechanical	SFRA, impedance, capacitance

Table 1: Transformer assessment tests.

Power Factor and Capacitance on windings and bushings

This test is used to assess the condition of the oil and cellulose in terms of moisture, carbonization, etc. The advantage of this method is that it identifies the winding (HV or LV) that has a possible problem.

Ratio test

This test is performed at 10 kV with a capacitor and is very effective in the detection of turn-to-turn or partial turn-to-turn failure when compared to other lower voltage (typically 380 V) ratio measurements. Experience has shown that

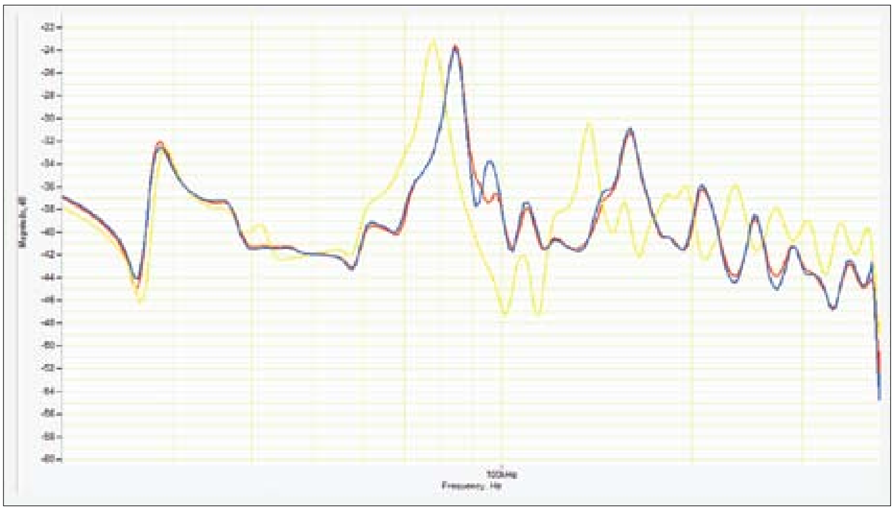

Fig. 4: HV to MV winding response.

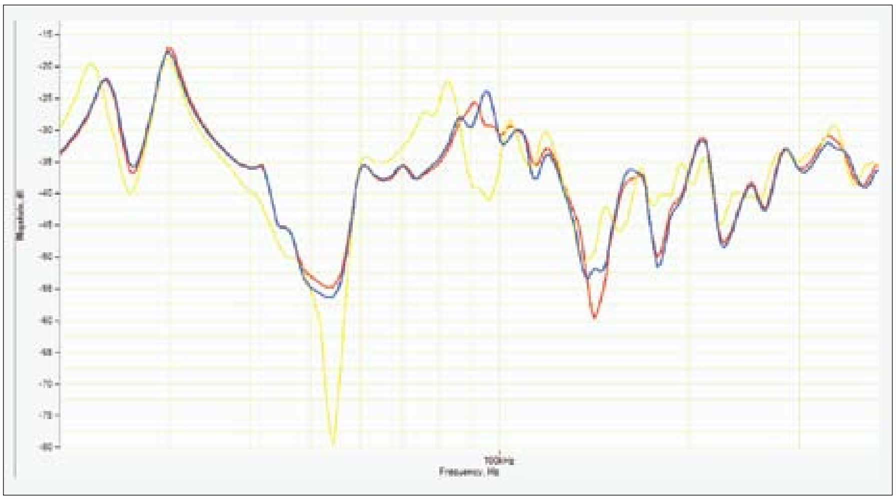

Fig. 5: MV winding to neutral response.

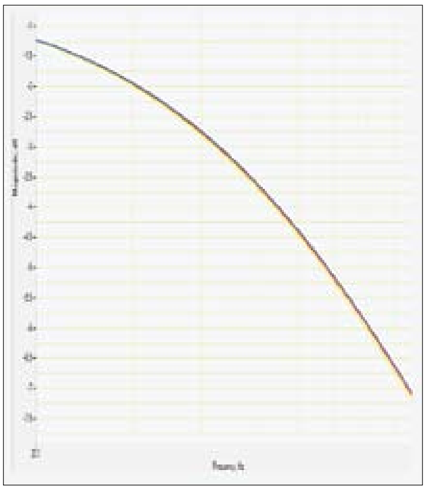

Fig. 6: HV Short circuit response.

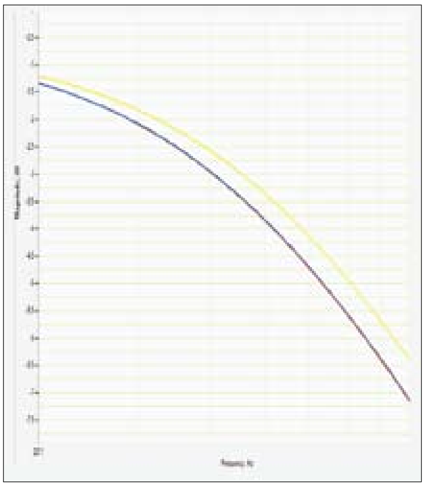

Fig. 7: MV Short circuit response.

low voltage ratio tests would not stress the insulation to a point were an inherent fault would be detected. If this fault remains undetected and the transformer is returned to service at a system voltage much higher than 380 V the transformer may fail on a turn to turn fault.

Excitation current test

This test is used to determine the condition of the magnetic circuit and the tap-changer. It is performed on all tap positions to identify a pattern in the currents. It is performed at high voltages (typically at 10 kV) as excitation current testing has proven to be ineffective in detecting core related problems at low voltages.

Insulation resistance test

This test is used to determine the condition of the insulation under the influence of a DC voltage. Measurements are from windings to ground and core to ground.

DC winding resistance rest

This test is used to determine bad or loose connections on tap changers, bushings, broken strands, shorted turns and high resistance contacts.

Impedance measurements

This test measures the short circuit impedance on a transformer as a 3-phase equivalent. Measured values are compared to nameplate values to assess the mechanical condition of the transformer in terms of winding deformation and core displacement.

Sweep frequency response analysis (SFRA)

This test passes a range of frequencies (between 10 Hz to 2 MHz) through the transformer and then calculates the transfer function. From these responses the mechanical condition can be assessed.

Transformer assessment

The transformer's condition can be accurately assessed by evaluating the transformer's thermal, dielectric and mechanical condition. This can be effectively done by considering the electrical and chemical tests. Table 1 indicates the tests that determine the transformers condition.

Case study 1

On 19 February 2007, a 275/132 kV, 315 MVA 3-phase auto transformer, manufactured in 1982, tripped on differential protection (red and blue phases), main tank and tap change pressure. At the initial site inspection, the blue phase pressure relief plate was found to have been blown out from the diverter head cover. The main tank pressure relief valve had operated. No other external damage was visible. Diagnostic tests and internal inspections were performed.

Diagnostic test results

- *Power factor and capacitance test:* Capacitances compared well with historical results and were not indicative of a problem. Winding power factor test showed a significant increase from the historical results. This is expected as the result of the main tank pressure relief operation.
- *Excitation current test:* The tests performed after the transformer had tripped indicated problems on the blue phase. When compared to historical test results, the blue phase exciting currents had increased by an average of 47%, indicating a tap-changer or short circuit problem.
- *Ratio test:* From the ratios measured, the blue phase had a number of taps not within acceptable limits. All of the electrical tests indicated a failure in the

tap-changer. This was clearly evident from the initial site inspection.

- *SFRA tests*: The SFRA results are given in Fig. 1. The HV to MV winding open circuit test shows a significant difference in the blue phase compared to the other two phases. This is a result of a possible shorted turn, which has the effect of creating an imbalance in the reluctance on one of the core limbs, producing this characteristic change in low frequency response. Excitation current and ratio tests supported this diagnosis. However, there is also a variance on the blue phase when compared to the other phases in the mid-to-high frequency range, which indicates winding deformation. This variance warranted an internal inspection.

Conclusions from test results

All the electrical tests pointed to a problem possibly limited to the tap-changer. However, the SFRA indicated clear winding/lead deformation on the blue phase. This was the result for the main tank pressure operating.

Internal inspection

The internal inspection revealed the following:

- *Diverter:* When removed from the transformer, the diverter was found to have a blown out pressure relief plate (incorporated in the head cover casting), and burnt flexible lead which connects metal parts to the common contacts which connect to the take-off terminal.
- *Internal inspection of selector:* The blue-phase selector revealed that the moving contacts were connected to terminals 5 and 6 whereas these are on terminals 6 and 7 on red and white phases, and there were severe burn marks due to flashover and arcing of fixed contacts and collector rings. See Fig. 2.
- *Windings in main tank:* Blue phase tapping leads and cleats had severe distortion of the tapping leads external to the windings, due to fault current forces, and paper insulation damage (Fig. 3). The condition of the MV winding could not be inspected. Numerous cleats and bolts were dislodged and broken and had fallen to the bottom of the transformer.

Conclusion

It was clear that the tap-changer had faulted. If the fault was restricted to the tap-changer, repairs would have been undertaken on site. This could have surely resulted in a further failure as a result of the tap-changer lead movement and damage to the windings as indicated by the SFRA. The transformer is due to be de-tanked and inspected in the factory.

Fig. 8: MV white phase.

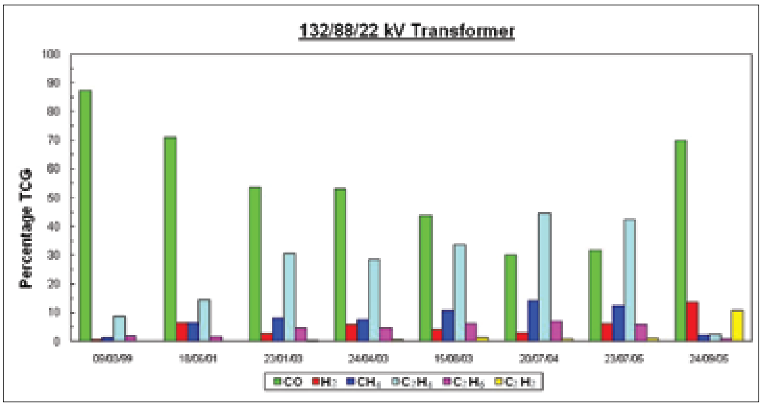

Fig. 9: DGA signatures.

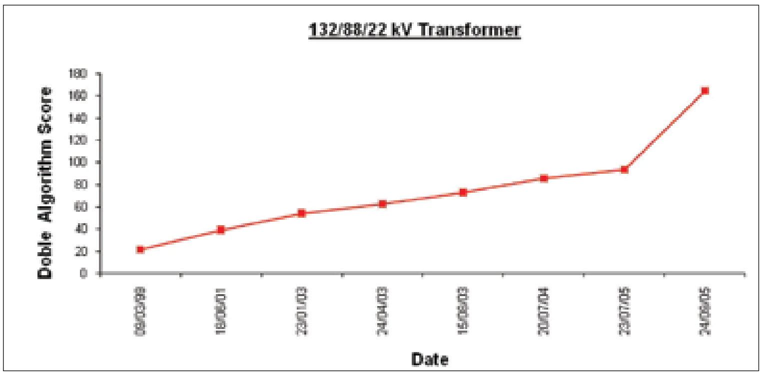

Fig. 10: Doble algorithm scores.

Case study 2

A 132/88/6,6 kV autotransformer, manufactured in 1982, and rated at 60 MVA underwent its routine maintenance tests.

Diagnostic tests performed

- *Power factor and capacitance test:* The power factor and capacitance test results were within acceptable limits.
- *Ratio test:* The ratio test results were within acceptable limits.
- *Excitation current test:* The excitation currents were within acceptable tests.
- *SFRA test*: The results are given in Figs. 4, 5, 6 and 7. The HV to MV winding open circuit response shows clear variances on the middle phase

Fig. 11: Uncorrected thermal fault.

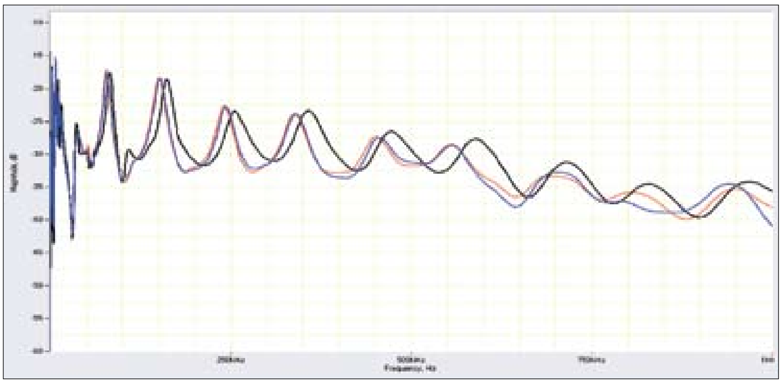

Fig. 12: LV winding response.

Fig. 13: Axial collapse.

at frequencies between 20 kHz and 400 kHz when compared to the other two phases, indicating hoop buckling. The MV winding to neutral open circuit response shows similar frequency shifts on the white phase at frequencies between 20 kHz and 400 kHz, indicating deformation in the MV windings. The HV and MV short circuit response revealed no resistance or impedance change between the phases. The MV short circuit test revealed a resistance and impedance change when compared to the other phases, a clear indication that the deformation is restricted to the MV winding.

Conclusion

The transformer was internally inspected and the MV winding had clear indications of winding deformation in the form of hoop buckling. This is shown in Fig. 8. In this case SFRA proved to be the only test that could detect this type of fault as all other electrical and oil tests gave no indication.

Case study 3

A 132/88/22 kV autotransformer, manufactured in 1982, and rated at 160 MVA tripped on 31 July 2005 on differential protection and restricted earth fault.

Diagnostic tests performed: DGA

The results are shown in Fig 9. The Doble Algorithm results are shown in Fig 10. From 1999 until 2005 the transformer experienced a localized thermal fault. This is signified by the high levels of ethylene and significant levels of methane and ethane. A DGA signature of this pattern indicates a core and frame to earth circulating current. The transformer experienced a dielectric fault on 24 September 2005. This is indicated by the levels of hydrogen and acetylene. The root cause of the transformer failure was the uncorrected thermal fault that was present since 1999.

Doble algorithm

Doble has developed an algorithm to mimic the key gas response and give a single number to track the change in pattern. This uses the key gas method to present DGA used by IEEE method. The relative proportions of the combustible gases CO, H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 are displayed as a bar chart to illustrate the gas signature. This method is used to investigate and illustrate the clear difference that exists between "normal" and "abnormal" results. The DGA score reflects the seriousness of the signature. DGA results for normal transformers would be expected to return a score of no more than about 30, whereas a core circulating current would rate about 60 and more serious problems would score around 100.

In this case study it is clear that the Doble algorithm identified the fault many years before the failure, and also indicates a steady increase in the scoring, which indicates a worsening condition.

Internal inspection

After the analysis of the DGA test results, an internal inspection was performed. The results are shown in Fig. 11.

Case study 4

A 132/11 kV transformer, manufactured in 1978, and rated at 30 MVA was taken out of service as a result of a Buchholz alarm. The DGA indicated a dielectric fault possible involving the winding. Apart from having elevated power factor results all other tests did not give a clear indication of the possible problem. The SFRA results showed a significant shift of a number of resonances for the C phase LV winding (Fig. 12). The transformer was removed from service and a tear down was performed. The internal inspection revealed an axial collapse of the C phase of the LV winding (Fig 13).

Conclusions

- The numerous diagnostic tools available to maintenance managers can be effectively used to monitor transformer condition, fingerprint healthy transformers and aid in effective analysis and identification of failures and failure mechanisms, aiding appropriate maintenance interventions.
- DGA interpretation in particular aids by differentiating between dielectric and thermal faults. The value of power factor, ratio tests, and excitation currents is once again verified and implemented to detect the cause and location of a fault. SFRA measurements have proved to be a reliable means of detecting winding movement damage, even if reference results are not available.
- Signatures prior to faults are useful for comparisons. Since opportunities for off-line diagnostic tests are rare and limited, it is essential that the most is made of any outage window of opportunity to perform the relevant tests.
- In general, the use of diagnostic test tools and techniques enhances the condition monitoring process for transformer, both when in service and when faulted, thus allowing for informed decision making by asset managers.

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